Bolometric Detectors for the High Frequency Instrument on the Planck[1,2]

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[1] 0-7803-7231-X/01/$10.00/© 2002 IEEE
[2] IEEEAC paper #399, Updated Oct 19, 2001

Abstract—The High Frequency Instrument (HFI) on Planck will obtain all-sky images of the Cosmic Microwave Background (CMB) and other astrophysical sources of emission with resolution of 9 arcmin at 100 GHz, 7 arcmin at 143 GHz and 5 arcmin at 217, 353, 545 and 857 GHz. The HFI focal plane will contain 48 silicon nitride micromesh bolometric detectors operating from a 100 mK heat sink. Four detectors in each of the 6 bands will detect the sum of the power in both linear polarizations. An additional 4 pair of detectors will provide sensitivity to linear polarization of emission at 143, 217 and 353 GHz. We report on the development of these detectors, which are being produced at the JPL Micro Devices Laboratory, packaged at JPL Electronics Packaging, characterized at 100 mK before delivery to our HFI consortium partners at the UWCC, UK.

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1. INTRODUCTION

Planck was selected in 1996 as the Medium Mission M3 of the Horizon 2000 Plan of the European Space Agency (ESA) (Figure 1). Planck is dedicated to obtaining definitive images of the Cosmic Microwave Background (CMB) fluctuations and to extract the primordial signal to high accuracy from contaminating astrophysical sources of confusion. Planck will make precise determinations of the fundamental cosmological constants which define our Universe, including the densities of baryonic, cold and hot dark matter, the value of the cosmological constant and the Hubble constant, and the neutrino content of the Universe. Planck will use two focal plane units: a Low Frequency Instrument (LFI) using High Electron Mobility Transistors (HEMTs) sampling the frequency range 30-100 GHz and a High Frequency Instrument (HFI) using bolometers, sampling in the frequency range from 100-857 GHz. Planck will be launched by an Ariane 5 launch vehicle into a halo orbit around the L2 libration point in the Sun-Earth system in 2007. The spacecraft will be spin stabilized with a spin rate of 1 rpm.

In response to ESA's Announcement of Opportunity (AO), Dr. Jean-Loup Puget of the Institute d'Astrophysiqe Spatiale (IAS) in Orsay, France submitted a proposal for the HFI which was selected as part of the payload for the Planck mission. As the Principal Investigator (PI) for the HFI, Dr. Puget will participate in the development, launch, post-launch and data analysis phases of the mission. Dr. Puget is responsible for the successful conduct of the HFI including the delivery, testing, integration and post-launch operation of the complete HFI. In this capacity, he is supported by Dr. Jean-Michel Lamarre, HFI Instrument Scientist, and Jacques Charra, HFI project Manager. Professor Peter A.R. Ade who is the HFI local Project Element Manager at University of Wales, Cardiff College responsible for assembly and testing of the focal plane of the HFI and subsequent delivery of the focal plane to IAS. PPARC will fund the HFI focal plane

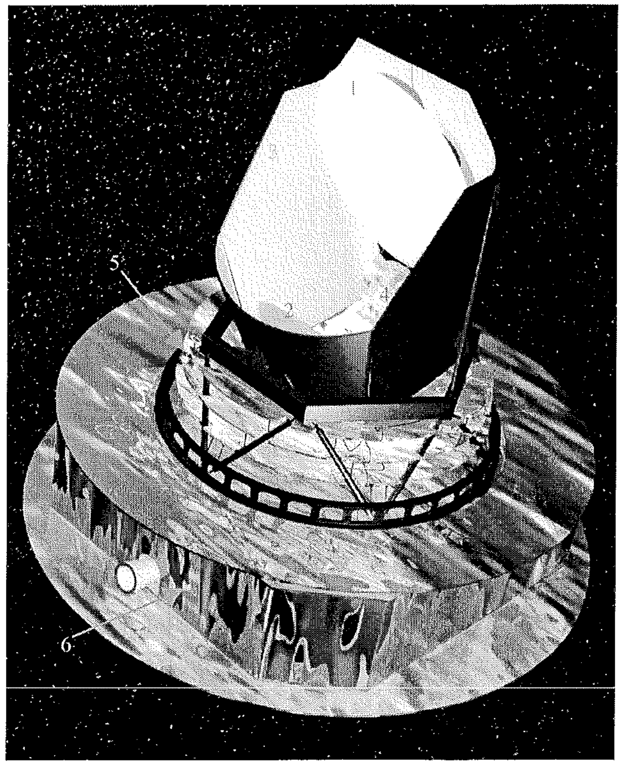

Figure 1 - Planck Spacecraft: 1) primary mirror; 2) secondary mirror; 3) stray light shield; 4) HFI and LFI focal plane; 5) V-groove radiators and 6) spacecraft bus.

assembly and testing at Cardiff, together with the 4 K Joule-Thomson cryocooler program of work at CLRC's Rutherford-Appleton Laboratory (RAL), and also the mission planning and data products contributions to Planck, which are being undertaken at the Imperial College of Science, Technology and Medicine (London) together with the Institute of Astronomy (Cambridge).

NASA/JPL is also providing the 18 K sorption cooler.

2. INSTRUMENT DESCRIPTION

The HFI is designed to measure the temperature anisotropy and polarization of the CMB radiation over the frequency bands where contamination from foreground sources is at a minimum and the CMB signal is at a maximum. Emission from foreground contributions (from the Galaxy and extra-galactic sources) will be removed from the sky maps by measuring the spectral signature of the fluctuations over a wide frequency range. The HFI is therefore a multiband instrument with 6 bands from 100 to 857 GHz. The focal plane is a layout of 48 bolometric channels in 36 pixels fulfilling all of the scientific requirements.

The HFI consists of (i) the HFI Focal Plane Unit (FPU), (ii) the JFET Box (iii) the Readout Electronics, (iv) the Data Processing Unit (DPU), (v) the Coolers, and (vi) harness and tubes linking various subsystems (Figure 2). It is based on the use of bolometers cooled at 100 mK. Bolometers are sensitive to the heat deposited in an absorber by the incident radiation. Very low temperatures are required to obtain a low heat capacity giving a high sensitivity with a short enough thermal time constant.

Cooling the detectors at 100 mK in space is a major requirement that drives the architecture of the HFI. This is achieved, starting from the passively cooled 50K/60 K stage of the payload module, by a four-stage cooling system (18K-4K-1.6K-0.1K). The 18 K sorption cooler is common to the HFI and the LFI.

The 4 K stage protects the inner stages from the thermal radiation of the 20 K environment. It also provides an electromagnetic shield (a Faraday cage) for the high impedance part of the Readout Electronics. The coupling of the telescope with the detectors is made by back-to-back horns attached on the 4 K stage, the aperture of the waveguides being the only radiative coupling between the inside and the outside of the 4 K box. Filters only are attached on the 1.6 K stage and bolometers on the 100 mK stage, this corresponds to an optimal distribution of heat loads on the different stages.

The HFI focal plane unit has an extension to the 18 K and 50/60 K stages, enclosing the first stage of the preamplifiers (J-FETs). The AC bias and Readout Electronics performs all the electrical functions of the cold stages, including the temperature measurement and control.

To control systemmatics, close-to-great-circle scans at 1 rpm are used requiring stability of the detector system on minute time scales and a speed of response <4 msec (16 mHz to 100 Hz) (Figure 3).

3. FOCAL PLANE

The HFI 100 mK Focal Plane Unit consists of 48 bolometer in 36 detectors and will be assembled at Cardiff. Each bolometer detector module will be mated to the 100 mK plate and to its respective 100 mK feedhorn. Cardiff is responsible for procuring and characterizing the feedhorns, harnesses and cryogenic testing of the entire focal plane which is then deliver to IAS (Figure 4).

JPL will be delivering detectors for three HFI models. Detectors with relaxed performance requirements are delivered for the Elegant Breadboard (EBB) and Cryogenic Qualification Model (CQM). Proto Flight Model (PFM) detectors of each frequency band and polarization type will fully comply with all requirements flowed down to the detectors and documented in the Business Agreement: “Detectors for the Planck High Frequency Instrument”. The PFM detectors will have undergone a full program of testing, electrical calibration and verification prior to delivery.

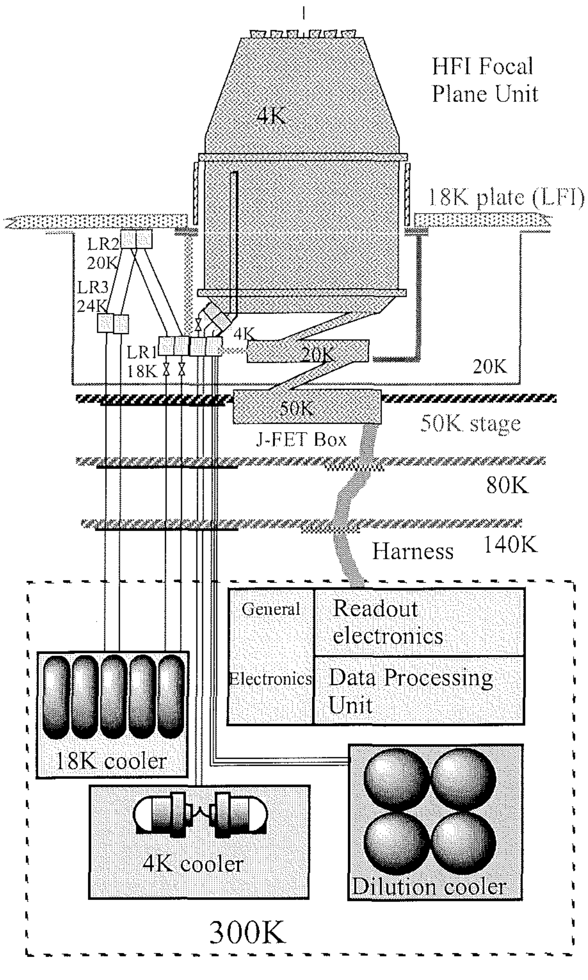

Figure 2 – Planck System

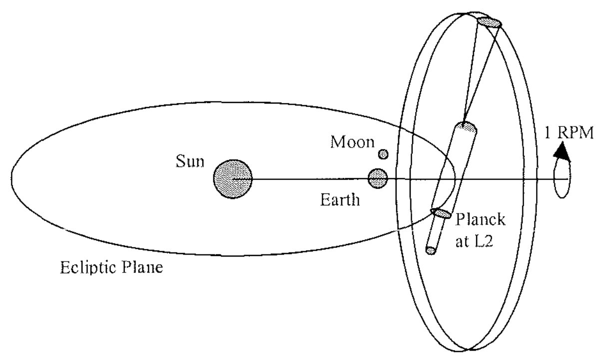

Figure 3 - Planck Scan Pattern

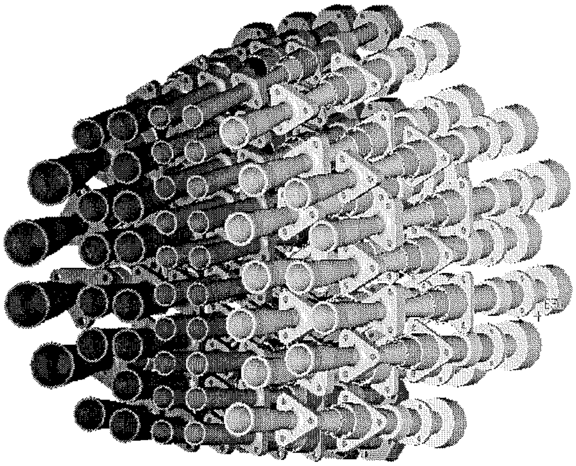

Figure 4 – Early configuration of the HFI Focal Plane showing the showing the back-to-back 4 K horns in the front and the bolometer modules with 100 mK horns in the back. Colored by frequency band.

4. Bolometer Fabrication

All of the silicon nitride micromesh bolometers are fabricated at JPL's Micro Devices Laboratory (MDL). This is a Develop New Technology (DNT), i.e. research oriented, as opposed to Develop New Product (DNP), i.e. production oriented, organization that has adopted facility and process improvements to accommodate a flight program.

All materials used in this program will have certifications and are used exclusively for the flight project. Travelers, procedures, traceability to manufacturers lots, etc., have been implemented. All personnel working on the project have taken the flight hardware and electrostatic discharge (ESD) classes and the facilities are certified for ESD and cleanliness. A program of facilities monitoring including particle detection, wafer particle detection, ESD control, designated locked flight cabinets and equipment calibration has been implemented.

The silicon nitride micromesh ("spider web") bolometer (SWB), technology developed for Planck will provide background limited performance in all bands. The radiation is efficiently absorbed in a conducting film deposited on a micromesh absorber, which is thermally isolated by radial legs of uncoated silicon nitride that provide rigid mechanical support with excellent thermal isolation (Figure 5).

The temperature of the absorber is measured by small (300x50x25 um) neutron transmutation doped (NTD) Ge thermistor that is indium bump bonded to and read out with thin film leads that are photolithographed on two of the radial legs. Compared to a solid absorber, the micromesh has a geometric filling factor of only ~1.5%, providing a correspondingly small suspended mass, absorber heat capacity and cosmic-ray cross-section.

Each polarization sensitive detector uses a pair of a new type of bolometer. These Polarization Sensitive Bolometers (PSB's) use identical fabrication processes as the SWB but have a new absorber geometry that makes them sensitive to only one linear polarization.

Micromesh bolometers are currently used in numerous CMB experiments (BOOMERANG, MAXIMA, SuZIE, Archeops) which operate under similar optical loading and detector sensitivity requirements to those needed here.

5. Bolometer Packaging

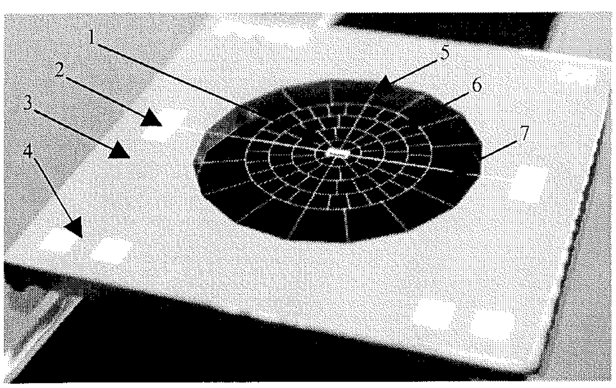

Figure 5 – Spider Web Bolometer: 1) NTD Ge thermistor on SiN island; 2) pad; 3) Si frame; 4) test bars; 5) SiN leg; 6) SiN web and 7) lead.

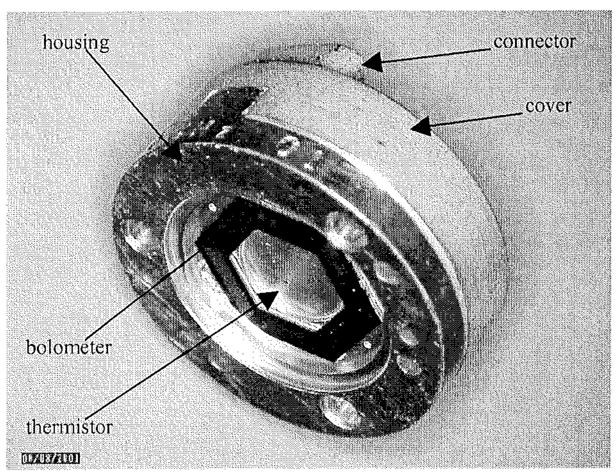

Figure 7 – SWB Module

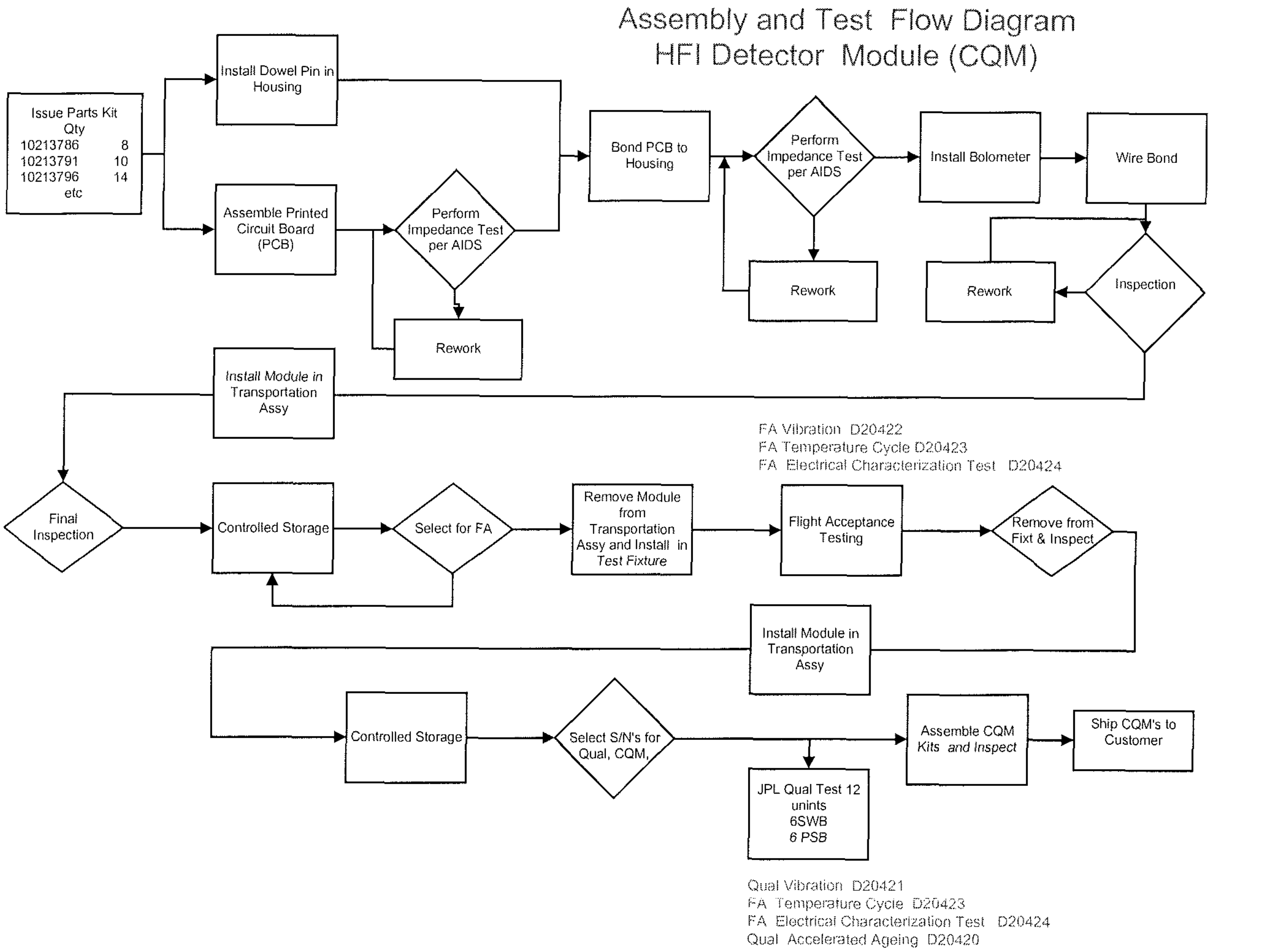

Figure 6 – Assembly Flow

JPL's Electronic Packaging (Section 349) packages the bolometers from the MDL into housings that provide a robust electrical and mechanical interface. This facility features controlled access, temperature controlled (72+/-3 deg), humidity controlled (30-70%), ESD certified hybrid lab in a class 10,000 cleanroom. Flight level process control is maintained for cleaning, adhesive bonding, wire bonding, gap welding, die attach, soldering, solder tinning, torque and mechanical assembly. Inspection and calibrated resistance testing is also provided. All mechanical parts plus printed wiring boards (PWB's) are procured and inspected by JPL. Discrete electronic parts were furnished by Caltech and are being upscreened at JPL as part of the detector Qualification program.

Figure 6 shows the assembly and test flow for the detector build from the mechanical parts and bolometer delivery from the MDL through delivery to Cardiff including the flight acceptance testing. All work is documented on Assembly Instruction Data Sheets (AIDS) as per JPL flight practice. Figure 7 shows a SWB mounted in it's detector module.

6. CHARACTERIZATION

Thermal Environment

Because the HFI bolometers operate at 100 mK, an Oxford Instruments Kelvinox-25 $^3He/^4He$ dilution refrigerator has been bought and instrumented to perform the necessary low temperature characterization of the detectors (Figure 8). Designed to accept up to 24 bolometers per run, all signal channels are characterized for electronic noise: <6 nV/√Hz and has demonstrated a total ~15 nV/√Hz (Johnson plus phonon) .

The thermal stability required for bolometer intrinsic noise determination is 40 nK/√Hz to 16 mHz. This is implemented via passive thermal design and active feedback using high resolution thermometry. A four stage structure creates passive thermal RC filters. Active control of a stage

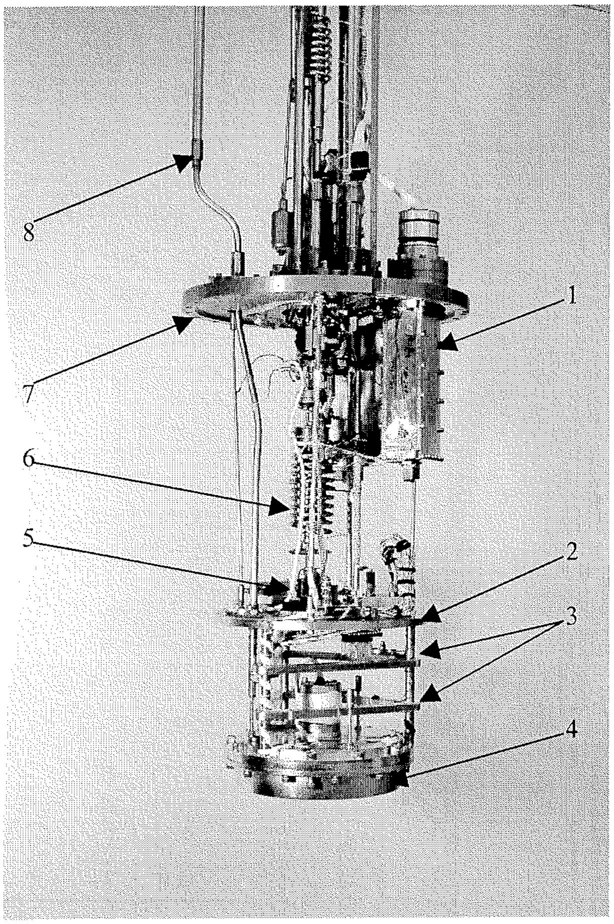

Figure 8 – 100 mK Test Bed: 1) JFET box; 2) 100 mK cold plate; 3) passive thermal filter stages; 4) evacuated sample can; 5) $^{3}He/^{4}He$ mixing chamber; 6) heat exchanger; 7) indium vacuum to LHe seal; 8) light pipe.

distributes the thermal noise power density spectrum over a wider bandwidth and modulation of the isolated stage where the detectors are mounted is reduced.

Optical Excitation: speed of response measurement

A bolometer's heat capacity (C~1 pJ/K) and the thermal conductance (G~100 pW/K) of it's link to the 100 mK thermal reservoir determine it's response. This bolometric response is modified from simple $\tau = C/G$ (~10 ms) by the weak electrothermal feedback of the thermistor, but essentially behaves as single pole rolloff. In order to measure the response to variable-frequency, constant-amplitude input radiation, a light pipe transports radiation from source outside the dewar at 300K to bolometers at 100 mK via a thin-wall stainless steel tube, gold-plated on the upper section. This technique has demonstrated that the optical response is due entirely to the bolometers.

Vibration Testing

Specialized fixturing holds up to three (3) "slices" of 8 bolometers per test run in a hermetic volume, opened only

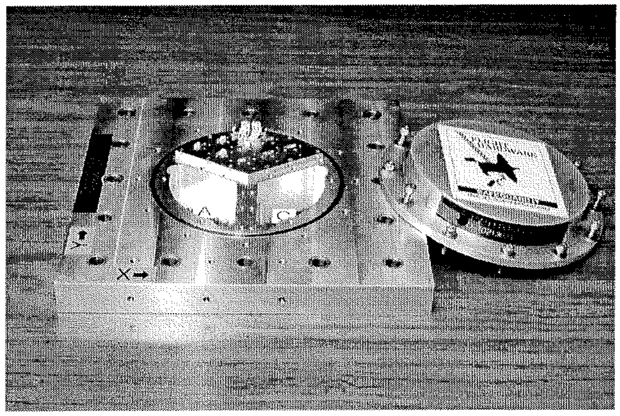

Figure 9 – 1 of 3 sample "slices" mounted on the vibration fixture with the hermetic cover removed.

under controlled conditions (Figure 9). The vibration tests are preformed at JPL or certified local test houses. The procedures are documented on AIDS forms approved and witnessed by JPL Quality Assurance.

Thermal Cycling

An LN2 cryogen dewar has been modified with a sample holder that can hold two (2) "slices" of 8 bolometers, a variable flow heat exchanger and heaters (Figure 10). Automated operation allows unattended thermal cycling. The resistance of each bolometer is recorded throughout the cycling intervals to a precision of 1%.

7. QUALIFICATION

Qualification Testing is performed on devices which have completed flight Acceptance Testing after which they are not flight deliverables. Twelve (12) detectors, 6 SWB (6 bolometers) and 6 PSB (12 bolometers), are taken as a representative sampling. Acceptance Performance Tests will then be repeated on all devices and the results will be evaluate for a Qualification report. The simple construction

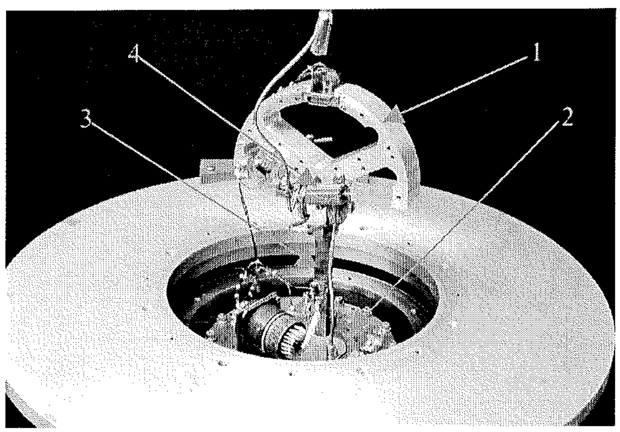

Figure 10 – Thermal Cycle Dewar: 1) 1/3 "slice" sample holder; 2) LN2 plate; 3) heat exchanger and 4) heaters.

of the detectors allows us to qualify the entire assembly as a hybrid.

Qualification vibration levels are specified in the Project Environmental Requirements Document (ERD) and the Business Agreement and are twice the Flight Acceptance levels.

The number of cryogenic thermal cycles for Qualification, 80, was chosen based on the estimates from various of our collaborators, indicating that the total number of cycles to cryogenic temperatures likely to be experienced by the Flight devices is ~25. The choice of cycling to a low temperature of ~90 K (LN2), rather than to the operating temperature of 100 mK or to 4.2 K (LHe), is based upon experience with similar devices which indicates that most failures occur during transition within this temperature range, and on general experience within the low temperature community that the majority of damage due to differential thermal contraction occurs within this temperature range.

Additional detectors will undergo Accelerated Aging (1000 hours, 85% RH, 70 C). Resistance will be monitored continuously. We have determined that the elevated temperature is not detrimental, however, we will be able to set limits on exposure to elevated humidity and take steps to control it.

8. SUMMARY

The strength of the scientific case for Planck is recognized both in Europe and in the USA. The detection of CMB anisotropies in 1992 by NASA's Cosmic Background Explorer (COBE) has opened up an entirely new way of studying cosmology to high precision. With the successful launch of the Microwave Anisotropy Probe (MAP) in June 2001, the next decade will see enormous experimental effort dedicated to mapping the CMB at increased sensitivities and angular resolution. Planck is the third generation CMB mission, after COBE and MAP, and will obtain definitive images of the CMB fluctuations and will be able to subtract primordial signal to high accuracy from the contaminating astrophysical sources of emission. This can be achieved by Planck which combines high resolution, high sensitivity ($dT/T < 3 \times 10^{-6}$ in each 7 arcmin pixel), wide frequency coverage and excellent control of systematic errors. This combination of requirements cannot be met either by ground-based or balloon-borne observatories and demands a space mission such as Planck.

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Andrew E. Lange is a professor at Caltech…

J. J. Bock *(Sta. Scientist, JPL/Ph.D. 1994, UCB) will play a key role in developing the silicon nitride micromesh bolometers, which he invented. He has 10 years experience in infrared optics, .lters, detectors, and cryogenics for space missions.*